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Temperature and strain gauge measurements in the TNO-PML Cook-off test

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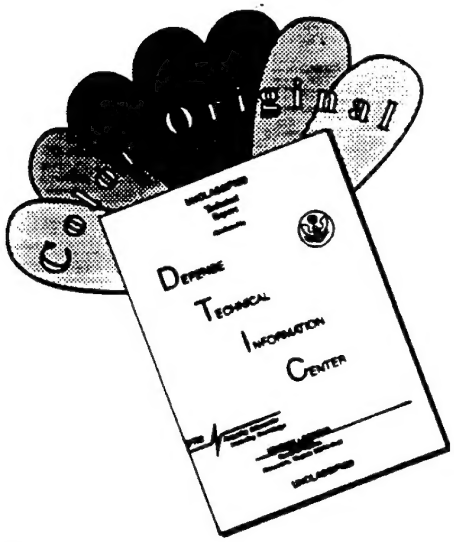

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Managementuittreksel

Titel	:	Temperature and strain gauge measurements in the TNO-PML Cook-off test
Auteur(s)	:	Ir. J.H.G. Scholtes, Dr. B.J. van der Meer
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Het moment en de mate van heftigheid in een 'Cook-off'-reactie wordt in sterke mate bepaald door een complex systeem van de opsluiting van de explosieve stof en de decompositie-/verbrandingssnelheid van de explosieve stof die tot een drukopbouw zal leiden. Het moment waarop het omhullende breekt waardoor drukaflaat plaatsvindt wordt bepaald door de sterkte van het omhullende materiaal. De snelheid waarmee deze decompressie plaatsvindt wordt bepaald door de concurrerende processen, de decompositie-/verbranding en de drukaflaat. Indien de drukaflaat groter is dan de drukopbouw zal het proces waarschijnlijk in een milde explosie/drukopbouw eindigen. Als daarentegen de verbrandingssnelheid voldoende hoog is zodat de gasgeneratie groter is dan de drukaflaat zal de druk blijven stijgen en bestaat er een redelijke kans op een deflagratie-detonatie overgang (DDT) of een heftige thermische explosie.

Wereldwijd wordt veel aandacht besteed aan het begrijpen van het 'Cook-off'-probleem en het bouwen van computermodellen die dit verschijnsel beschrijven. De testen die daarentegen op dit gebied uitgevoerd werden en worden zijn veelal gericht op de temperatuur en het tijdstip waarop de thermische wegloopreactie eindigt in een reactie. Naast de slecht gedefinieerde rand- en begincondities, leveren deze testen geen data aan waarmee de bestaande computermodellen geverifieerd kunnen worden. Daarom is TNO Prins Maurits Laboratorium (TNO-PML) rond 1987 gestart met de ontwikkeling van een 'Cook-off'-test die wel aan deze eisen zou voldoen.

Na de verschillende 'Cook-off'-testmodellen waarmee naast goede opsluiting en goed gedefinieerde opwarmsnelheid, interne temperatuurmetingen mogelijk waren, is de aandacht verschoven naar 'het meten van de mate van heftigheid'. Omdat op het TNO-PML veel expertise aanwezig is op het gebied van rekstroken, wordt onderzocht in hoeverre met deze techniek de rek/reksnelheid van het metalen omhulsel tijdens de explosie gemeten kan worden.

Naast een aantal deflagratie-/detonatietesten (DDT), waarbij de respons van rekstroken bekeken is, is er ook een aantal volledig geïnstrumenteerde 'Cook-off'-testen met rekstroken uitgevoerd. De DDT-testen waren bedoeld om te onderzoeken of de verschillende niveaus van heftigheid, drukopbouw, deflagratie en deto-

natie, met een rekstrook gemeten zouden kunnen worden. In een van de DDT-testen zijn tevens ionisatiepinnen gebruikt om te onderzoeken of het tijdstip van de respons van een rekstrook samenvalt met het langskomende verbrandings/drukfront. Verder is in de 'Cook'-off-testen gekeken in hoeverre met temperatuur gecompenseerde rekstroken de respons tijdens een 'Cook-off'-test gemeten kan worden. Door de hoge temperaturen tussen de warmtespiraal en de beperkte ruimte stelt dit namelijk hoge eisen aan de gebruikte rekstroken.

Uit de DDT-testen blijkt dat de minimale 'sample rate' ongeveer 5 Mhz moet bedragen om de rek/reksnelheid van het omhullende materiaal tijdens een detonatie te kunnen volgen. Tevens blijkt uit deze metingen dat er een goede trend waarneembaar is in de reksnelheid van de rekstroken in de verschillende fasen van een DDT-reactie. Klaarblijkelijk kan er aan de hand van rekstrookmetingen verschil gemaakt worden in de verschillende niveaus van heftigheid. De responsies van de rekstroken in een Cook-off test zijn nog niet kwantitatief te interpreteren. Wel geven de resultaten aan dat een mogelijke kwantitatieve bepaling van de heftigheid van een 'Cook-off'-reactie met rekstroken mogelijk zou moeten zijn. De metingen van de interne temperatuurgradiënten zijn van dien aard dat zelfs processen als smelt, kristal fase-overgangen en thermische ontleding, waargenomen kunnen worden. De testresultaten kunnen daarom een grote bijdrage leveren aan de opbouw en verificatie van nieuwe en bestaande computermodellen.

Contents

1 Introduction

The moment and the severity of a Cook-off event is determined by a tightly coupled and complicated system of the confinement of the explosive substance and the decomposition/combustion rate of the explosive substance resulting in a pressure loading. Due to the decomposition and eventually combustion of the explosive substance, the pressure starts to rise inside the cylinder. The pressurisation rate can increase due to a decomposition/burn rate enhancement. This enhancement is the result of cracks or defects and pores created by thermal stress and pressure waves. The burning and decomposition rate also depend highly on the pressure. So an increase in pressure results in an increase in the burning and decomposition rate. The pressure at which the confinement vents and starts to unload is controlled by the strength of the confining material. The rate of pressure release is affected by the coupling of the combustion/decomposition rate and the venting rate. If the venting rate is higher than the rate of gas generation, the pressure decreases, resulting in a mild explosion. If, on the other hand, the combustion rate is sufficiently high that gas generation is still higher than the gas release, the pressure still rises and the probability of a Deflagration to Detonation Transition (DDT) or a severe thermal explosion is high.

World-wide, much effort is being put into Cook-off modelling of energetic materials in a confined geometry. Modelling this complex mechanism involves the coupling of thermal, chemical and mechanical computer codes. In the past, Cook-off modelling was mainly focused on the thermal runaway of the reaction. Data were obtained by measuring the time and temperature to Cook-off in fast and slow Cook-off tests. Due to bad boundary conditions and the lack of information about the temperature distribution inside the test item, these data were not suitable for computer input. Therefore, TNO-PML started the development of a new midsize Cook-off test during the late eighties [1, 2]. One of the objectives of this new test was to fill the lack of experimental data suitable for verification of Cook-off computer codes. Therefore, a measurement of the temperature distribution in a system with well-defined boundary and initial conditions was necessary. Because the reaction level of a Cook-off off test highly depends on the level of confinement of the explosive substance, much effort is put into the development of the end-caps. During the years of development, modifications were made to the caps to assure the confinement during testing [3].

Lately, the interest in Cook-off modelling has been more and more focused on the mechanic-dynamical part of a Cook-off process determining the level of severity of the reaction. For this an experimental verification of the computer model is even more important. Therefore, the main effort in the development of the TNO-PML Cook-off test is emphasised on the strain and velocity measurement of the surrounding material during the end phase of the Cook-off event.

Because much expertise on strain gauge measurement is available in our division, we decided to explore the usability of strain gauges for our strain/velocity measurements in the Cook-off test. The work was carried out under assignment A95KL408.

Several tests with explosive substances have been performed with the TNO-PML Cook-off tube with full instrumentation. To measure the response of a strain gauge in several types of reactions, some DDT and detonation tests were performed. In the detonation experiments, we planned to measure a real detonation response. The reason for doing the DDT experiments was to measure the response along the tube at several different levels of reaction: the tube bulging (mild reaction) in the initial phase of the DDT process, a deflagration response (intermediate reaction) during the accelerating phase in the centre of the tube and a detonation response at the end of a DDT process near the end of the tube. These tests have been carried out with the same tube as the Cook-off tests, but the instrumentation for heating and temperature measurement was removed.

In Chapter 2, the experimental set-ups for the different tests with the Cook-off tube are given. In Chapter 3, a description of the tests with the corresponding test results are given, followed by the conclusions in Chapter 4.

2 Experimental set-up

2.1 Standard Cook-off test set-up

Because several types of experiments were carried out, several configurations of the TNO-PML Cook-off test set-up were used. In report [3], a full description of the latest version of the Cook-off test without strain gauge instrumentation is given.

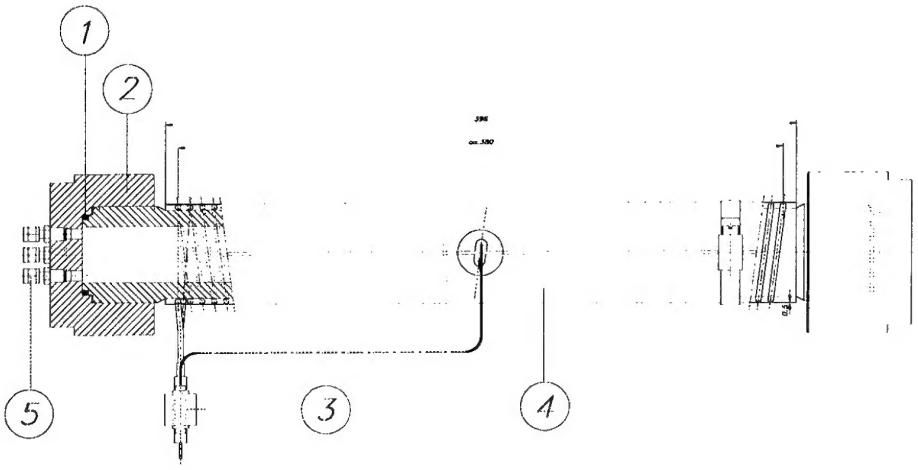

Figure 1: *The TNO-PML Cook-off test tube.*
1 Copper sealing ring
2 Screwcap
3 Heater with power connection
4 Steel cylinder
5 Thermocouple feed-through

In Figure 1, the design of the Cook-off test tube is shown. A steel cylinder (Euro norm Fe510) is used with a wall thickness of 10 mm over the total length of 500 mm and an inner diameter of 35 mm (outer diameter 55 mm). The inner volume of 480 cm^3 is closed at both ends with specially constructed steel end-caps (Euro norm Fe490). In the construction of the end-caps, a soft copper ring is included to ensure the confinement of the explosive substance during the experiment, the copper ring is deformed into its plastic region with a specially constructed torque wrench. With this cap construction, the cylinder can withstand internal pressures up to 240 MPa.

For heating, a nine-metre long heating wire (Pyrotenax) connected to the temperature controller is helically wrapped along the total length of the cylinder. Conducting sealant is added between the helical loops to improve the distribution of heat flow from the heating wire to the steel cylinder.

One end-cap is provided with four thermocouple (TC) feed-throughs. The end-tips of the TCs are positioned half-way along the cylinder at different locations in the radial direction. The second end-cap is, if desired, provided with a pressure transducer. Normally, five TCs are used for measuring the temperature distribution. Four are positioned in the interior of the cylinder and one is positioned outside the cylinder, on the tube wall. A sixth TC is used for controlling purposes and is also connected outside the cylinder. In our latest experiments, a seventh thermocouple is located at the outer corner of one end-cap.

The signal from each TC is fed into a linear isolation amplifier (Burr-Brown PCI 5B47K-05). Besides signal conversion, the isolation amplifier is necessary to protect the computer and electronic system against any possible unwanted high voltages from accidental contact with the main voltage after an explosion. Subsequently, the signal is fed into an analogue to digital converter (ADC) to convert the signal into digital data. These data are saved on hard disk. For data-acquisition and hardware communication, the computer program 'Labtech Note-book', also supplied by Burr-Brown, is used. With this program the real-time time-temperature curves of the TCs can be measured, saved and shown on the monitor.

For controlling purposes, one TC is fed back to an adjustable temperature controlling unit that controls the power to the resistance wire and therefore the supplied heat to the test object. With this programmable heat controller it is not only possible to heat the test object at a constant rate, but also a programmed temperature trajectory can be followed.

2.2 Strain gauge implementation

In this series of tests, strain gauges have been used to measure the strain/velocity of the confining material (steel tube) during an event. The operation of an electrical-resistance strain gauge is based on the principle that the electrical resistance of a conductor changes when it is subjected to mechanical deformation. The strain gauge is implemented in a bridge circuit and the change of the deformation-resistance is measured using a bridge amplifier, resulting in a voltage signal. If the strain gauge is connected to a steel cylinder and the change in resistance as a function of the deformation is given, the strain of the cylinder can be measured during testing.

The strain is measured in real-time in Cook-off experiments at high temperatures and in DDT and detonation experiments. Therefore, two different types of strain gauges are used in the experiments. A normal type strain gauge ('TML' YL-10) with a gauge dimension of 10 x 3 mm (base of 20 x7 mm) and a strain limit of 10-20% at a temperature of between -20 to 50 °C. This strain gauge is only used in the DDT and detonation experiments. This type has been used because it has a high strain limit and is relatively long. For the Cook-off experiments, special strain

gauges (M&M WK-06-125AD-350) have been used. This type of strain gauge is small (base dimension 10.2 x 5.6 mm) and can be placed locally in between the heating wire. This type has an operation temperature range from -269 °C to 290 °C and is still operational for temperatures up to 370 °C for short-term exposure. Besides the extreme operation temperature range, this type has an internal temperature compensation, minimising the temperature dependency of the strain measurement. The strain limit of this strain gauge is 1.5% at room temperatures up to 3% at 205 °C.

For an experiment, the location for the strain gauge on the steel cylinder is cleaned and roughened before the gauge is glued onto the tube. In Figure 2, a schematic representation of the locations (numbers 1 and 2) of the strain gauges in the Cook-off experiments is given. This drawing also gives the locations of the strain gauges in the detonation experiment.

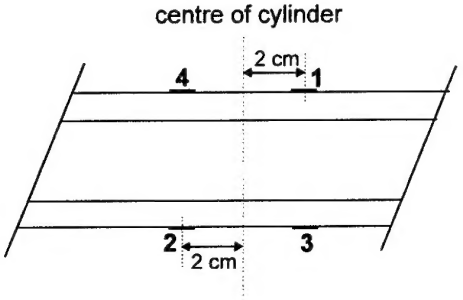

Figure 2: Location of the strain gauges on the steel cylinder in the Cook-off and detonation experiments.

In the Cook-off experiments, only high-temperature strain gauges are used at locations 1 and 2, 2 cm from the centre of the tube, and a rotation angle of 180°. In the detonation experiment four strain gauges were used. Numbers 1 and 4 are the large type gauges, and numbers 2 and 3 the small type gauges.

In the DDT experiments, two different types of configurations were used. The first configuration is shown in Figure 3. The strain gauges are positioned equidistantly on the cylinder at 9.5 cm. The bottom locations, numbered 1 to 5, are the small type, high-temperature gauges, and the top locations, numbered 6 to 10, are the long, high-strain limit types.

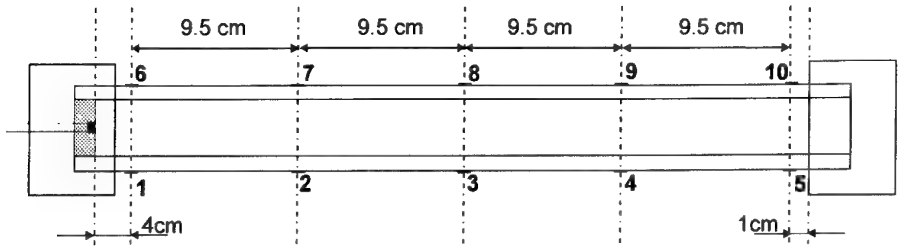

Figure 3: Location of the strain gauges in the first configuration of the DDT experiment. The numbers represent the location of the strain gauges.

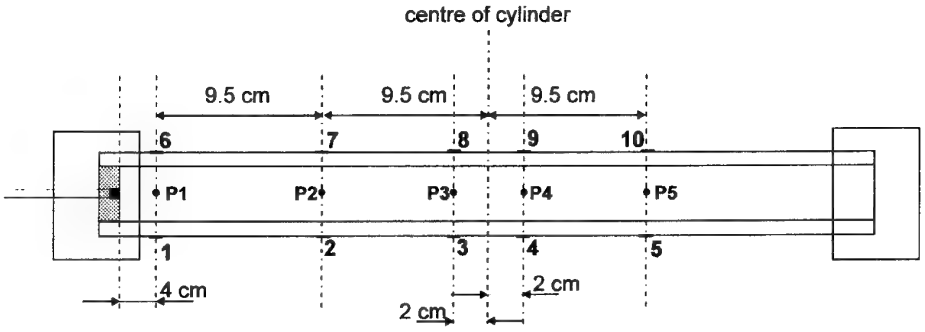

Figure 4: Location of the strain gauges in the last DDT experiment. The numbers 1 to 10 represent the locations of the strain gauges, while the numbers P1 to P5 represent the locations of the ionisation pins to trigger the detonation front during the DDT experiment.

The last configuration is shown in Figure 4. In this configuration, the gauges in the centre of the tube have the same locations and are of the same type as the gauges in the Cook-off configuration. The other strain gauges have the same location as in the first DDT experiment, but are of the long, high strain limit types. To know the exact time the detonation front passes the strain gauge position, at the end of the DDT reaction, five ionisation pins were installed.

3 Experiments and results

3.1 Introduction

As already mentioned, different types of experiments were carried out to measure the response of a cylinder equipped with a strain gauge during an explosive event. Because of the experience we have obtained with Hexocire (95% RDX, 4.5% wax and 0.5% graphite) in DDT research over the last few years, this explosive was used in all DDT and detonation experiments described in this report. For the instrumental Cook-off experiments, four types of explosive substances were used, as we intended to measure different responses in severity. A standard HMX-HTPB PBX, a cast TNT, AMPA (a composition of 80% AN, 10% TNT and 10% Al) and Permit B were used. A mild reaction was expected using the HMX-based PBX, an intermediate violent response with TNT and a detonation with Permit B and AMPA.

The preparation of the strain gauge experiments is relatively easy. At the locations of the strain gauges, the cylinder wall is roughened and cleaned before the gauges are glued to the cylinder. Then, the cylinder can be filled with loose Hexocire (density 1.0 gr/cm^3). After filling, a PVC cup with igniter substance and a bridgewire is placed in the cylinder and the steel cap is screwed on the cylinder. Now, the test object is placed in the explosion-safe bunker. The strain gauges are connected to the bridge amplifiers and the igniter is connected to the electric current power source. After the test facility is closed, and all safety precautions are taken, the test is carried out.

Preparation of a Cook-off experiment is a much more time-consuming and an accurate task. First, the locations of the strain gauges are roughened and the inner thermocouples are placed inside the tube through the first cap. Then, the cap with the thermocouples and a copper sealing ring is placed on the cylinder, torqued and welded. A large torque wrench has been constructed to deform the 50 mm copper rings into the plastic region. Now, the heating wire is helically wrapped around the tube leaving a space of 15 mm for the strain gauges at the predefined locations. The strain gauges are glued to these spots and the tube is heated for a few hours at a temperature of 50 °C above the maximum expected temperature during testing. Then, the space between the windings of the heating wire is filled with a heat conducting sealant to increase the homogeneity of heating. After this process, the cylinder is filled with the explosive substance and the second cap with the copper ring is placed and torqued on the tube. This time, the cylinder together with the torque wrench are placed in the bunker for safety reasons. After preparation, the test object is ready for testing. All connections are made and Cook-off testing can be started.

In the following paragraphs, the results of these series of experiments are given: firstly the results of the pure strain gauge measurements; then, the strain gauge results in the completely instrumented Cook-off experiments; and finally the temperature distribution curves of these Cook-off experiments.

3.2 Strain gauge measurements in DDT and detonation experiments

To measure the response of a strain gauge induced by different phases of a DDT, two DDT and one pure detonation experiment were carried out. The DDT experiments were initiated by a pyrotechnic mixture located in a PVC holder at one end of the tube (Figures 3 and 4). The detonation experiment was initiated by a standard U8 igniter. In Figure 5, the result of the first DDT strain measurement with the configuration of Figure 3 is given. The time is given in ms along the x-direction, the strain in μm/m is given along the left axis and the time derivative of the strain is given along the right axis. The sample rate of all channels was 1 MHz. Because channels S7-S10 did not give much information, their derivatives are not shown in the figures. Analysing the curves, it can be stated that the 1 MHz sample rate is not sufficient for this kind of experiment. Except for channels 1 and 6, the maximum of the strain is reached within a few samples. Only the bulging process of the tube at the beginning of the DDT process can be measured at this rate. The difference in response in time between channels S1 and S6 is not clear. It is probably due to the time base difference of the counter devices with an unknown cause.

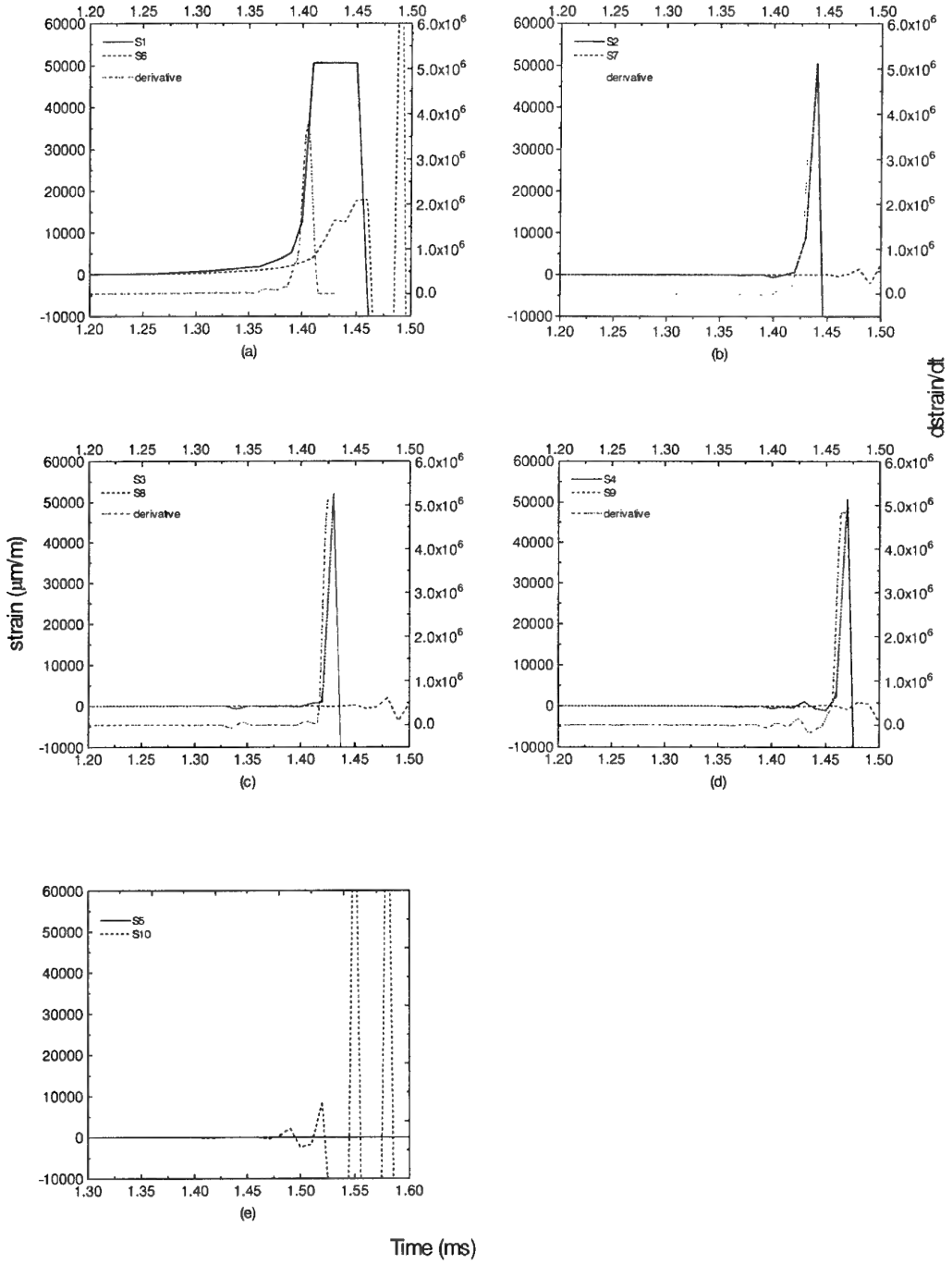

Figure 5: The responses of ten strain gauges at five different locations in a DDT experiment.

In Figure 6, the results of the second experiment in this series are shown. This experiment was initiated with an initiator. The time is given in μs along the x-direction, and is measured at a sample rate of 5 MHz. The curves shown in Figure 6 should be the results of a pure detonation experiment. In the upper graph

(channels S1 and S3), besides a sinusoidal disturbance, a relatively slow increase in the strain is shown in the first phase of the process, followed by a fast increase at the end of the process. In channel S2, in the lower graph, the disturbance of the signal is to large too deduce information about the first phase of the signal. The peak at the end of the curve is probably the result of a passing detonation front. Taking the time between the two peaks of signals S1 and S2 and the distance between the two strain gauges, a velocity of about 6 km/s is found, so the front must be a detonation front.

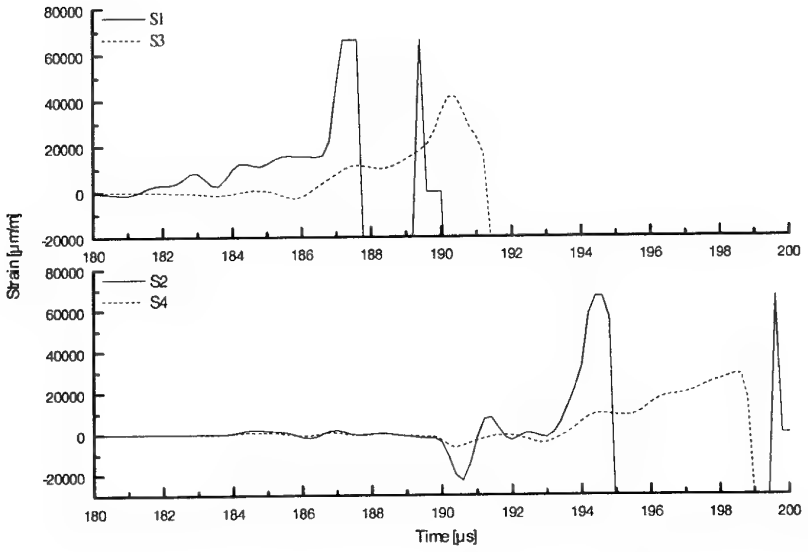

Figure 6: Response of stain gauges in a detonation experiment.

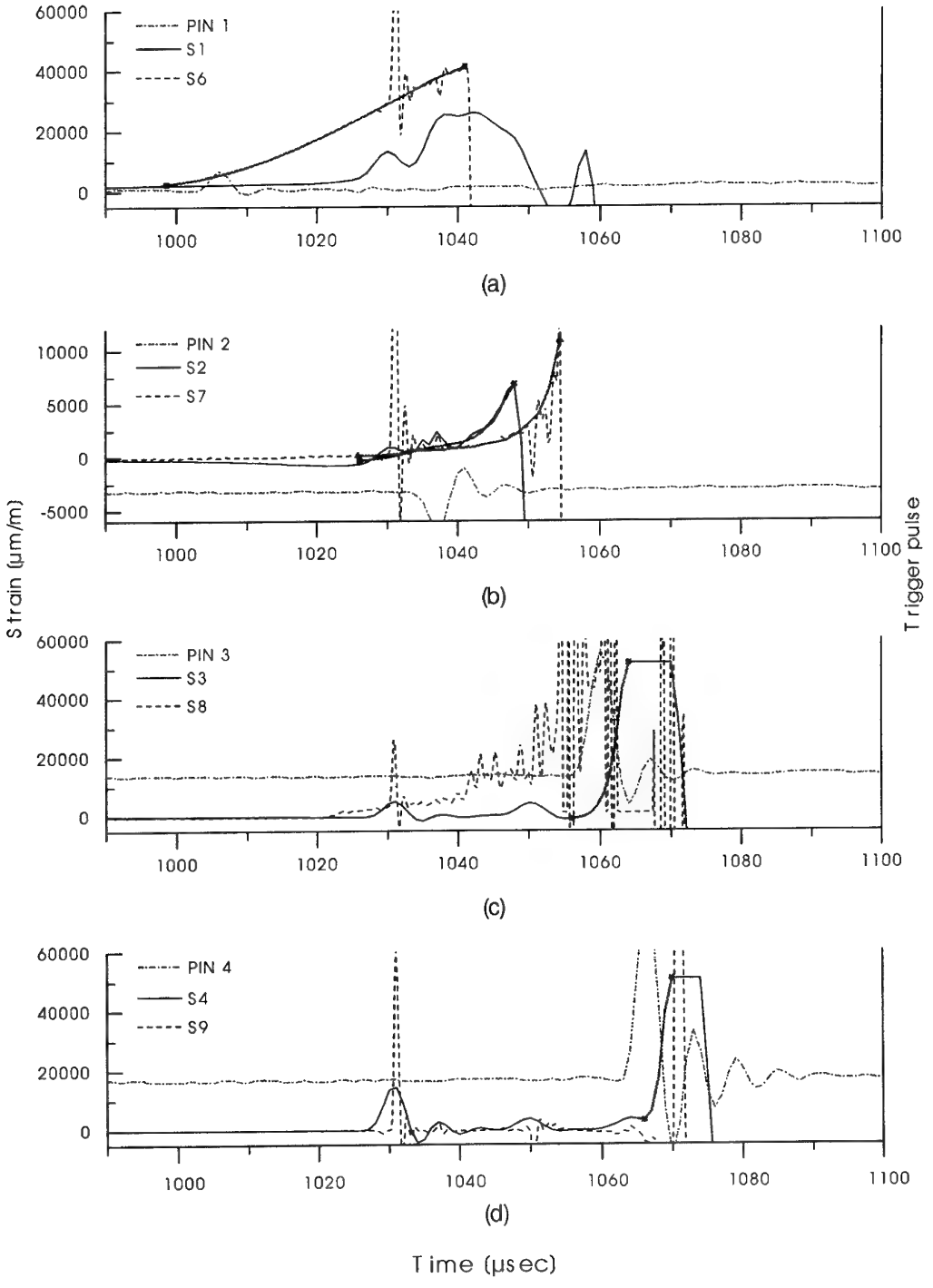

Figure 7: *Response of strain gauges in a DDT experiment. The upper curves give the response of the bulging process, the second graph the response of the build-up phase of the deflagration and the last two graphs are the results of a detonation.*

In Figure 7, the result of the last experiment in this series is shown. The graphs show the results of the experimental configuration in Figure 4. In this experiment, ionisation pins were used to follow the deflagration/detonation front passing along the strain gauges. In Figures a-d, the passing front is shown by the trigger pulse of the ionisation pins. In between pins 3 and 4, the front has a velocity of 5.7 ± 0.7 km/s. A computer calculation with the 'Tiger code' predicts a detonation velocity of 6.0 km/s for a density of 1.0 g/cm^3 for Hexocire (95% RDX and 5% wax). Although a lot of disturbance is shown on the signals, a trend of the increasing strain rate can be seen in the figures. The slope of the strain in figure (a) (between 1000 and 1040 µs) is relatively small and is due to pressurisation of the starting deflagration process. In figure (b) (9.5 cm after pin 1 in Figure 4), the strain rate has increased, which is shown by the increase of the slope between 1025 µs and 1055 µs. The last two figures (c, d) are the results of the strain gauges about 7.5 and 4 cm further along the test tube (and of pins 3 and 4 in Figure 4); the slope of the strain increases even more. In these last figures, the front has the detonation velocity and the slope of the strain gauges must be the response of a detonation. In Annex A, Photo 2 shows the fragmentation of the tube after this experiment. On the left side in the photo, the long fragments are certainly the result of a deflagration and the small fragments starting around the centre are the fragments of a real detonation. A good explanation for the difference in time between corresponding channels, like S1 and S6 etc., cannot be given. A non-homogeneity of the tube or a difference in the time base of the counters can be a reason for this time shift of the response.

3.3 Strain gauge measurements in Cook-off experiments

In this paragraph, the results of the strain gauge measurements in the Cook-off experiments are given. Four different experiments were carried out, all with a different explosive, an HMX-based PBX (85% HMX), TNT, Permit and AMPA (81.2% AN, 10% TNT and 8.8% Aluminium). The pre-set heating rate of all experiments was 0.05 °C/s. Due to a bad thermocouple connection to the temperature controller in the first experiment with HMX-PBX, the strain gauge data-acquisition was not on standby. Therefore, only temperature data are available for this experiment.

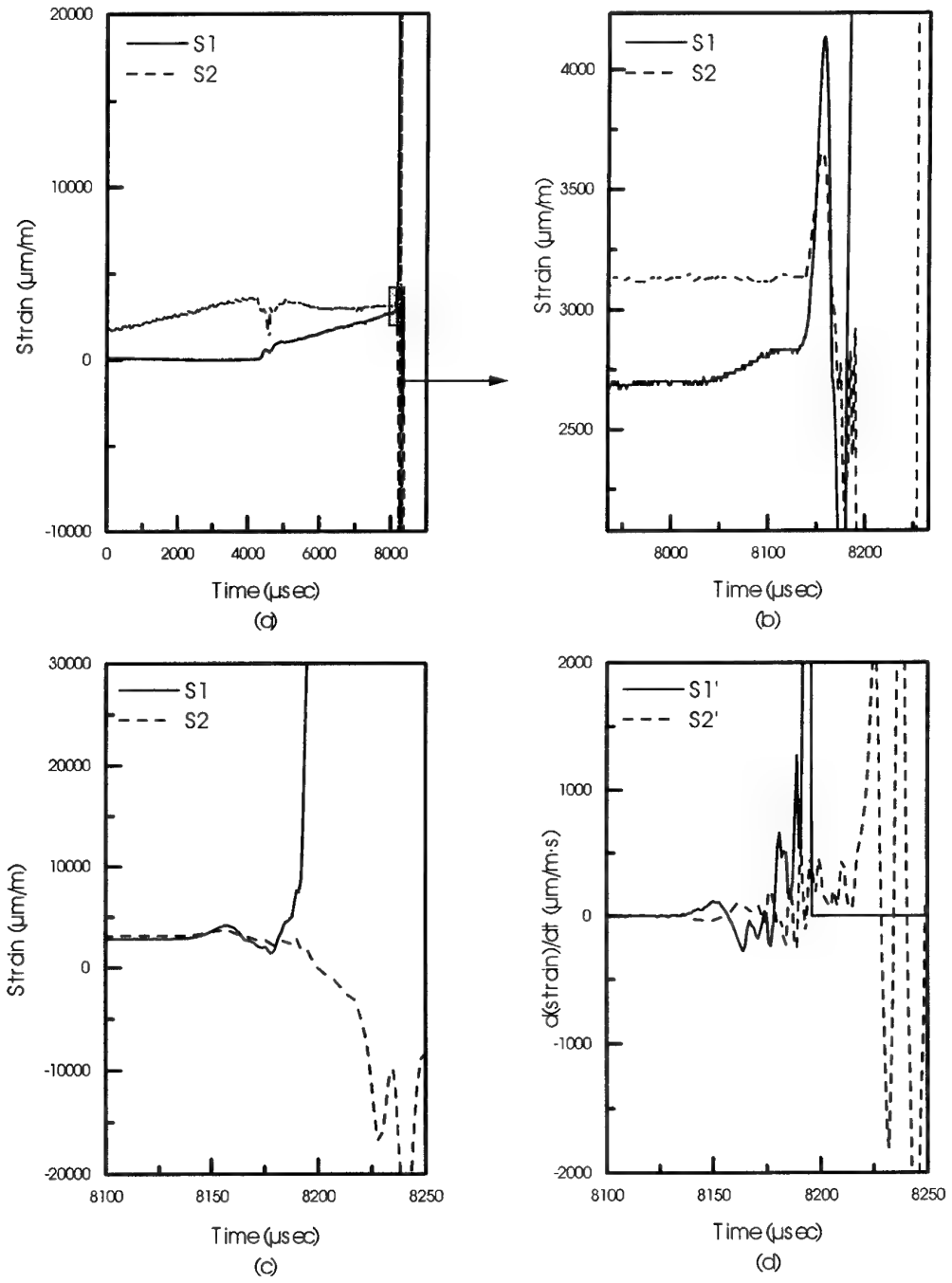

Figure 8: Results of strain gauge responses of a Cook-off experiment with TNT.

In Figure 8, an overview of the strain gauge measurement of the TNT experiment is shown. The response of the TNT was very mild. Due to a pressure build-up, the tube burst in the centre. In the upper left graph, Figure 8a, a total time of about 9000 µs is shown. A magnification of a small window of this graph is shown in

Figure b. A magnification of this time region, but with strains up to 30000 μm/m, is shown in Figure c. The time derivative of Figure c is given in Figure d. At this time, an interpretation of these figures is not possible.

In Figure 9, the results of the strain gauge measurement of Permit are given. In the upper graph, the strain is given as a function of time. In the lower graph, the derivative of the strain is given as a function of time. The maximum in the derivatives is around 600 μm/s m. The fragmentation of the tube is shown in Photo 3 in Annex A. Only the second half of the tube is fragmented into a few pieces, while the first half remained in one piece.

In Figure 14, the strain results of the AMPA Cook-off test are shown. Like the Permit experiment, the strain and its derivatives are shown in the graphs. This time the maximum in the derivative is about 900 μm/s m; 1.5 times the value of the Permit experiment. The fragmentation of the experiment is shown in Photo 4 in Annex A. This time more fragments over the total length of the tube were found after the experiment.

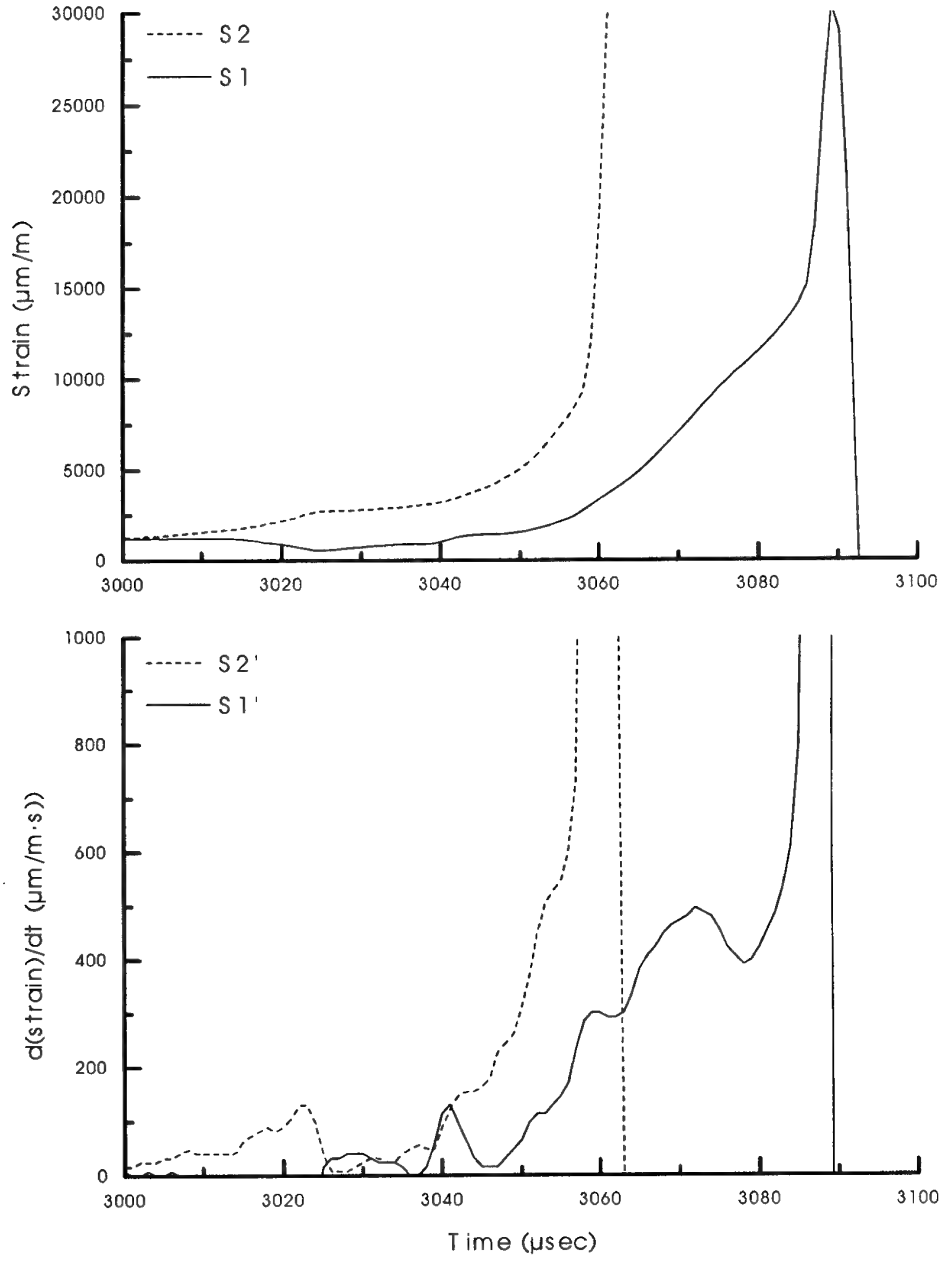

Figure 9: *Strain and its derivative as a function of time in a Cook-off experiment with Permit B.*

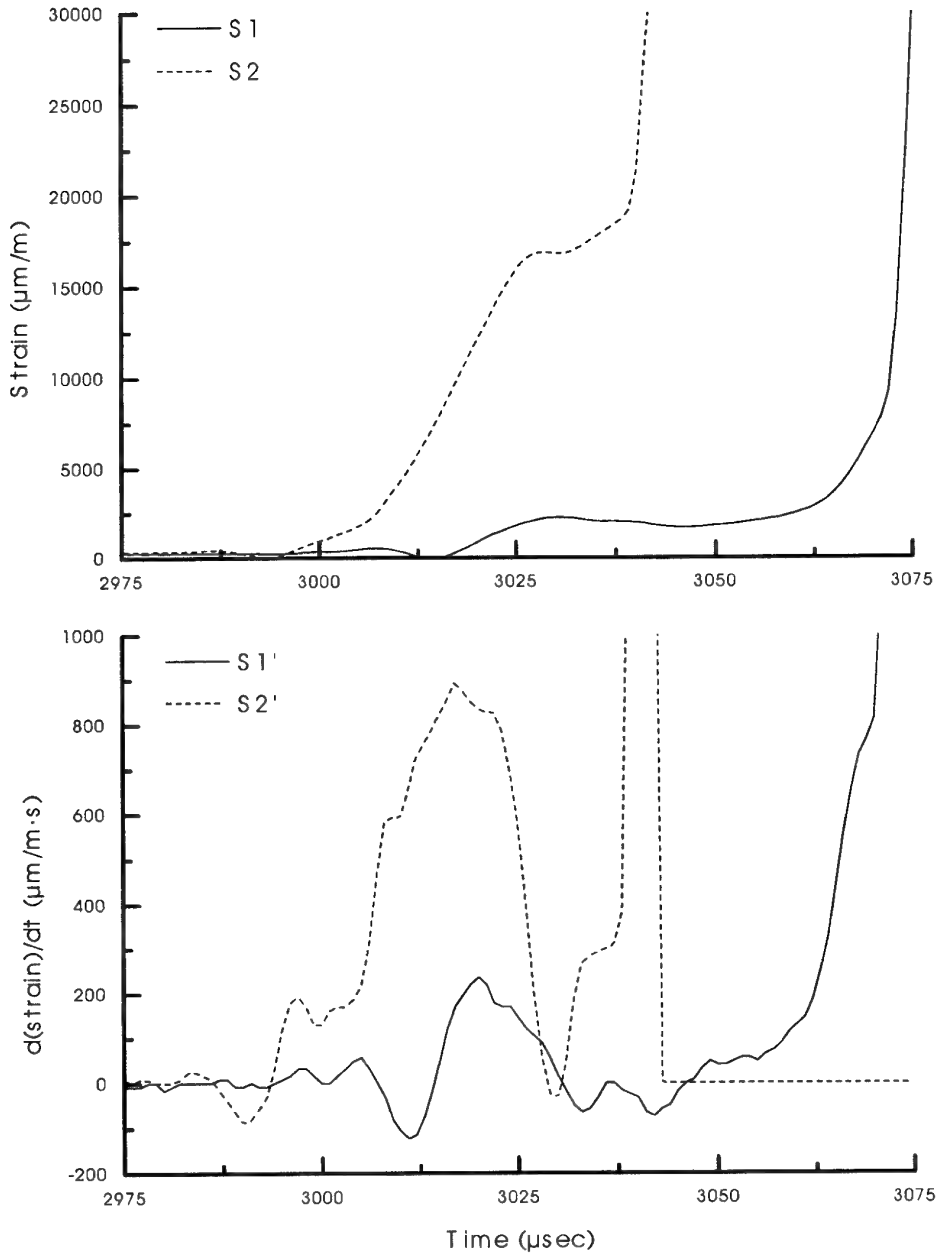

Figure 10: Strain and its derivative as a function of time in a Cook-off experiment with AMPA.

3.4 Cook-off temperature measurements

The temperature measurement of the first Cook-off experiment with HMX-PBX shows better results than the strain measurement. But because of the loose contact of the controller thermocouple, the strain measurement failed. In Figure 11, the temperature curves of this experiment are shown. The magnification of this graph, is shown in the lower graph. The loose contact is shown by the fluctuation of the temperature measured by the controller thermocouple and the temperature on the tube wall. Compared with the other curves, the fluctuation is very large. Also the temperature measured by the thermocouple located inside the tube, 1.31 cm from the centre of the tube (T131), is higher than the wall temperature, which confirms this assumption. Deduced from theory and the temperatures of the internal thermocouple, the estimated wall temperature is given in curve 'T_{est}'. The estimated wall temperature at the time of explosion lies between 225 °C and 229 °C. The corresponding heating rate is 0.057 °C/s. The estimated heat conduction coefficient is 0.31 ± 0.011 J/sm^{2}K in the range between 90 °C and 195 °C (Annex B). The bottom curve in the upper graph is the temperature of the cap. Comparing this curve with the other cap temperature of the other experiments, the estimated explosion temperature was 225 °C.

In Figure 12, the temperature distribution curves of the TNT experiment are shown. As mentioned before the preparation of the Cook-off experiment is an accurate task. During the preparation of the TNT experiment, two thermocouple connections were damaged. The only internal thermocouples that worked were at a distance of 1.31 cm and 0.87 cm from the centre line. The experiment was carried out at a heating rate of 0.05 °C/s. After 2500 seconds, all TNT had melted and the temperature gradient decreased. At about 3500 seconds, a non-linearity was measured by the two internal thermocouples. An explanation for this curvature is an endothermic bond breaking reaction of TNT followed by a exothermic reaction near the end of the experiment, and finally the tube burst at 4150 seconds [5].

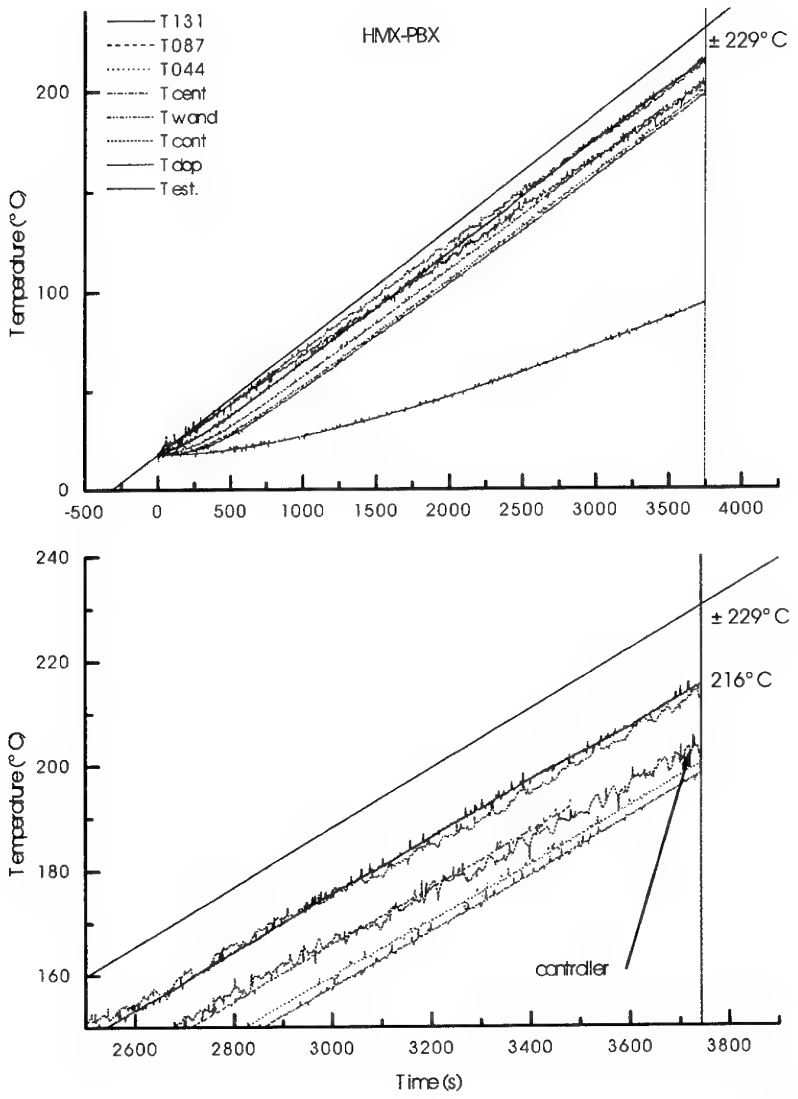

Figure 11: In the upper graph the temperature distribution of the Cook-off experiment with HMX-PBX. In the lower graph, a magnification of the last 1000 seconds.

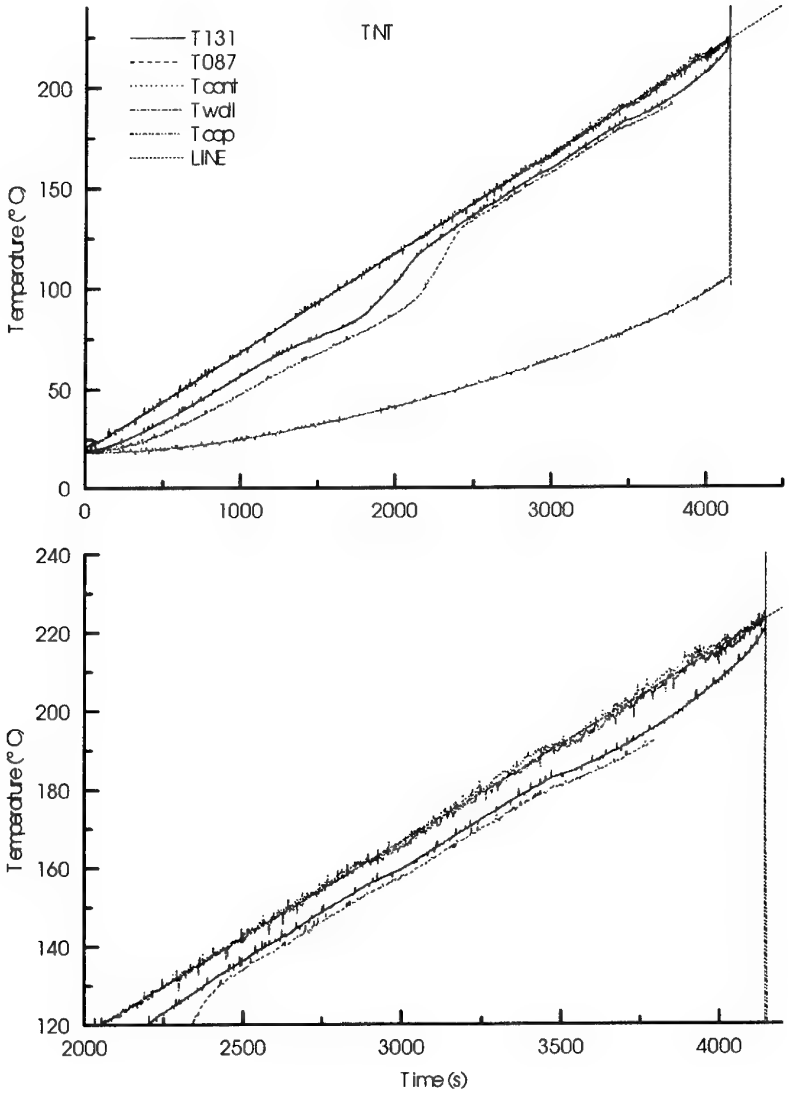

Figure 12: In the upper graph, the temperature distribution of the Cook-off experiment with TNT. In the lower graph, a magnification of the last 2000 seconds.

In Figure 13, the temperature distribution curves of Permit are shown. The heating rate of the experiment is 0.05 °C/s. After a rather smooth heating, an exothermic reaction starts at about 2800 seconds, resulting in a fast temperature increase of the explosive substance. At 3000 seconds, the experiment is ended by an explosion of the tube at one half of the cylinder. That half of the tube fragmented into six large pieces, while the other half remained in one piece.

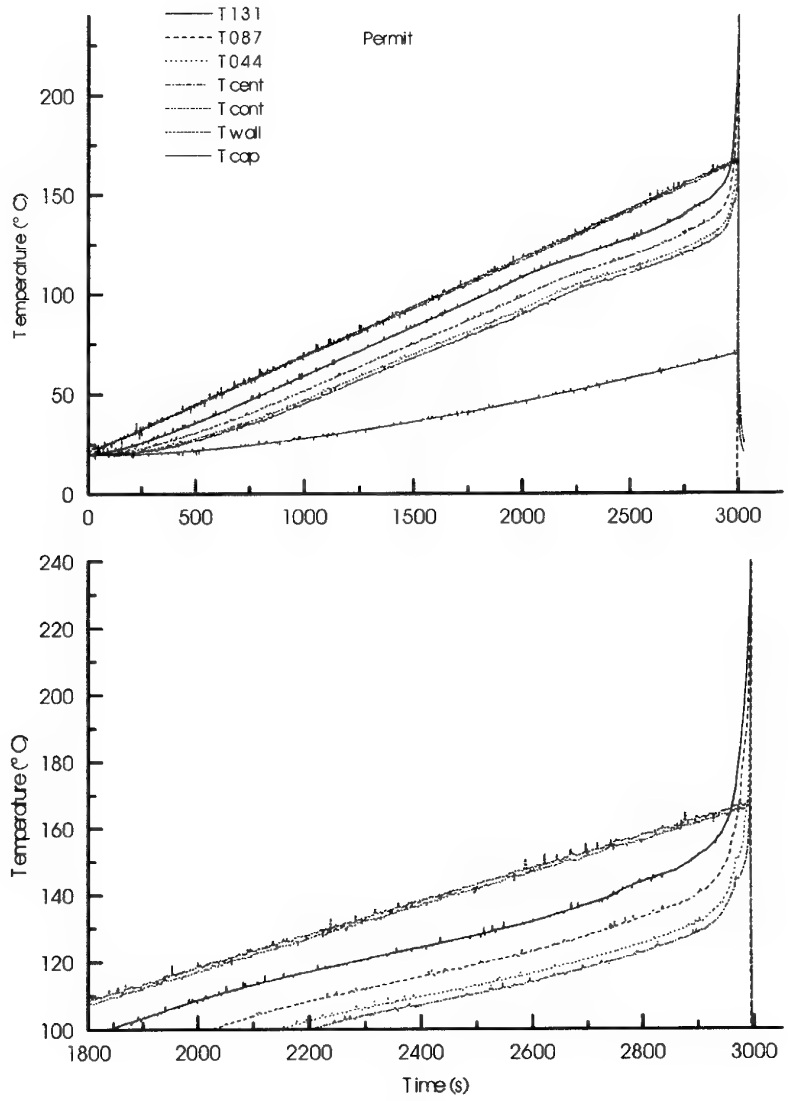

Figure 13: In the upper graph, the temperature distribution of the Cook-off experiment with an Permit B. In the lower graph, a magnification of the last 1000 seconds.

The last figure, (14), is the most interesting one, which is the result of the Cook-off experiment of AMPA. AMPA is an explosive substance containing 81.2% AN, 10% TNT and 8.8% aluminium.

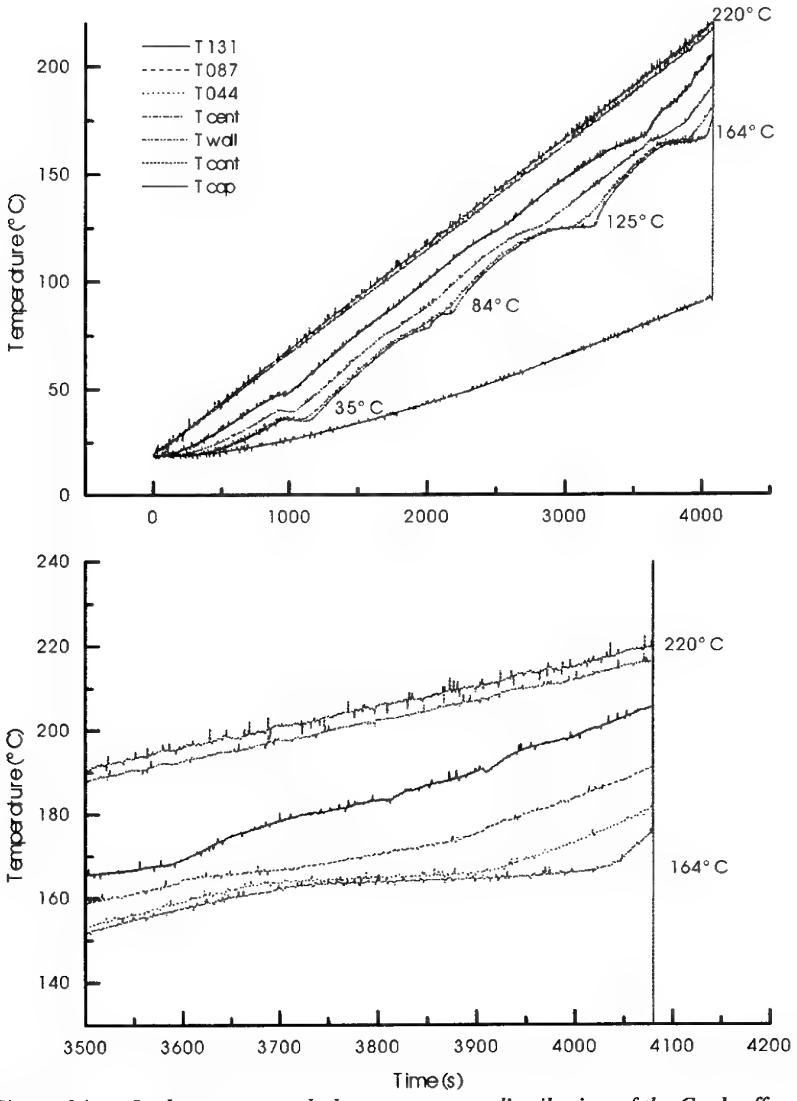

Figure 14: In the upper graph the temperature distribution of the Cook-off experiment with AMPA. In the lower graph, a magnification of the last 700 seconds.

Four crystalline phase transitions can by found in this curve, especially near the centreline of the tube. Normally, the phase transitions are:

- IV → III 32.1 °C
- III → II 84.2 °C
- II → I 125.2 °C
- melting 169 °C

Due to additives, the transitions can change to a different temperature. The transition from phase IV to III is not very clear and lies around 34 °C in the experiment. At a temperature of about 80 °C, a small change in the linearity is shown which can be ascribed to the melting of TNT in the explosive substance. The transition from phase III-II is found at a temperature of 84.9 °C, but is much smaller. The transition from phase II-I is very obvious and is shown at a temperature of 125.2 °C. The melting phase is located at a temperature of 164 °C and is probably decreased due to additives in AN. After 4080 seconds, the experiment is ended by an explosion which fragmented the tube into more than twenty pieces of steel. This experiment was also carried out at a heating rate of 0.05 °C/s.

4 Conclusion

Several tests have been performed with the TNO-PML Cook-off tube. The first measurement showed that a sample rate of 1 MHz is not sufficiently high enough for a strain rate measurement. The results of the DDT experiments showed that the slope of the strain coincides with the pulse of the ionisation pins. So, the bulging process of the tube is really measured by the strain gauges. From this measurement it is also evident that there is a trend in the strain rate in the deflagration to detonation region. So, several responses of the severity from a pressure burst up to a detonation should be measurable using the strain gauge technique at elevated Cook-off temperatures.

Although no quantitative interpretation of the strain gauges responses in a pure Cook-off experiment can be given yet, the results look very promising. Besides some minor perturbations of the controller thermocouple in the first experiment, the results of the temperature measurement in the Cook-off tests are very useful for comparison with computer model results. Also from these data, parameters like the conductivity coefficient can easily be obtained. Also the more complex calculation processes like endothermic debonding and runaway reactions, melting phases and crystal phase transitions are shown in the distribution curves. Therefore these results can serve as a tool to validate the Cook-off computer codes.

After these first promising strain gauge results in a real-time Cook-off experiment, more experiments will be performed to quantify the severity of a Cook-off response. For comparison reasons, pressure transducers will be used in one of the end-caps in future experiments. This way the pressure inside the tube can be measured during the Cook-off process. Hopefully this will lead to an even better verification experiment for Cook-off computer models, which will lead to a better understanding of the Cook-off process before and during the Cook-off event.

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6 Authentication

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Annex A Cook-off tube and fragmentation

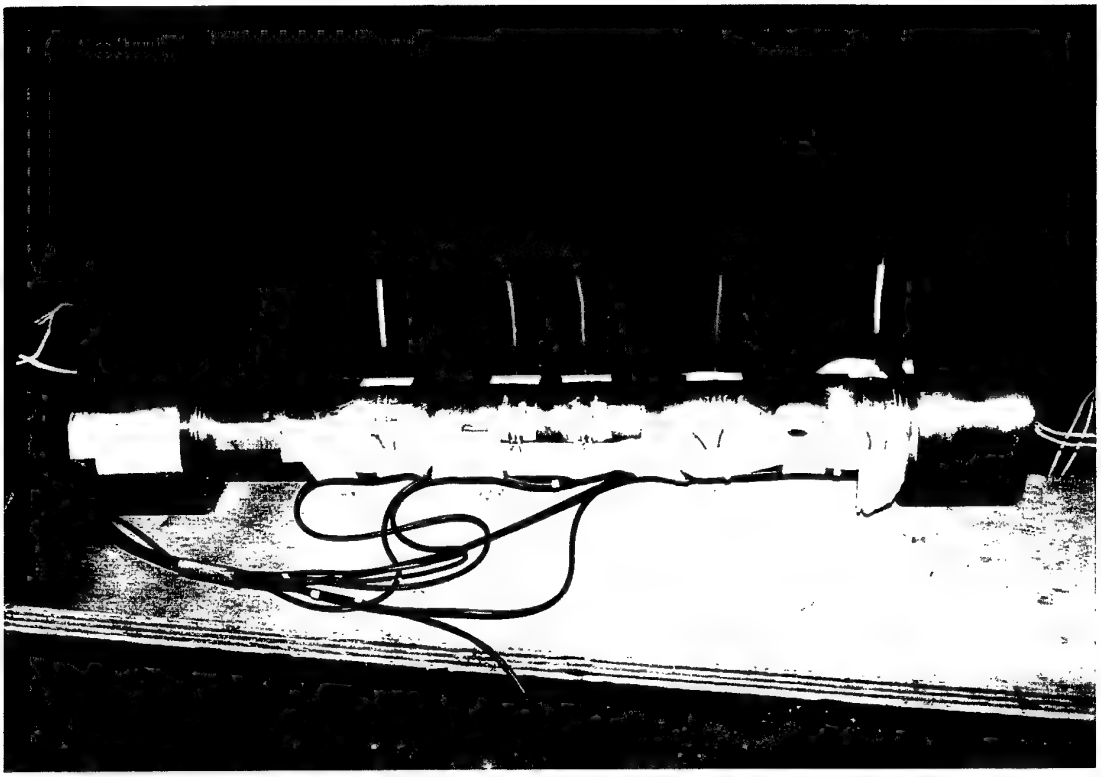

Photo A.1: Photo of the TNO-PML test tube with the strain gauges and ionisation pins before the experiment.

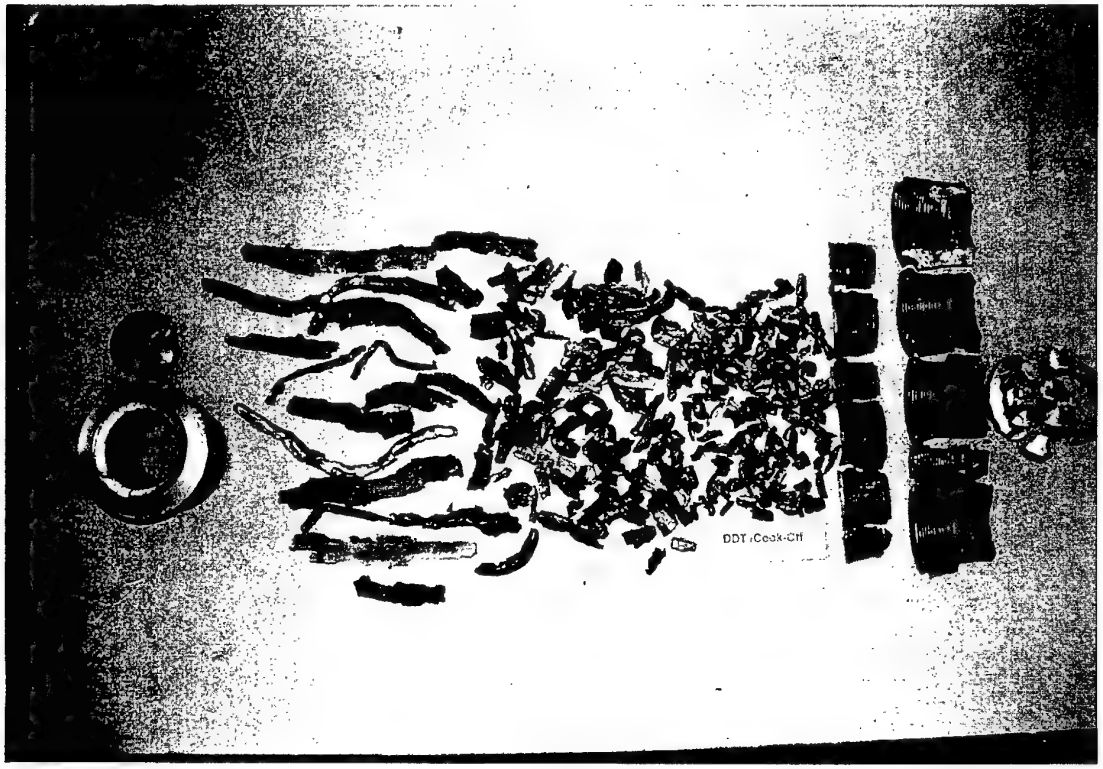

Photo A.2: Fragmentation of DDT experiment with Hexocire.

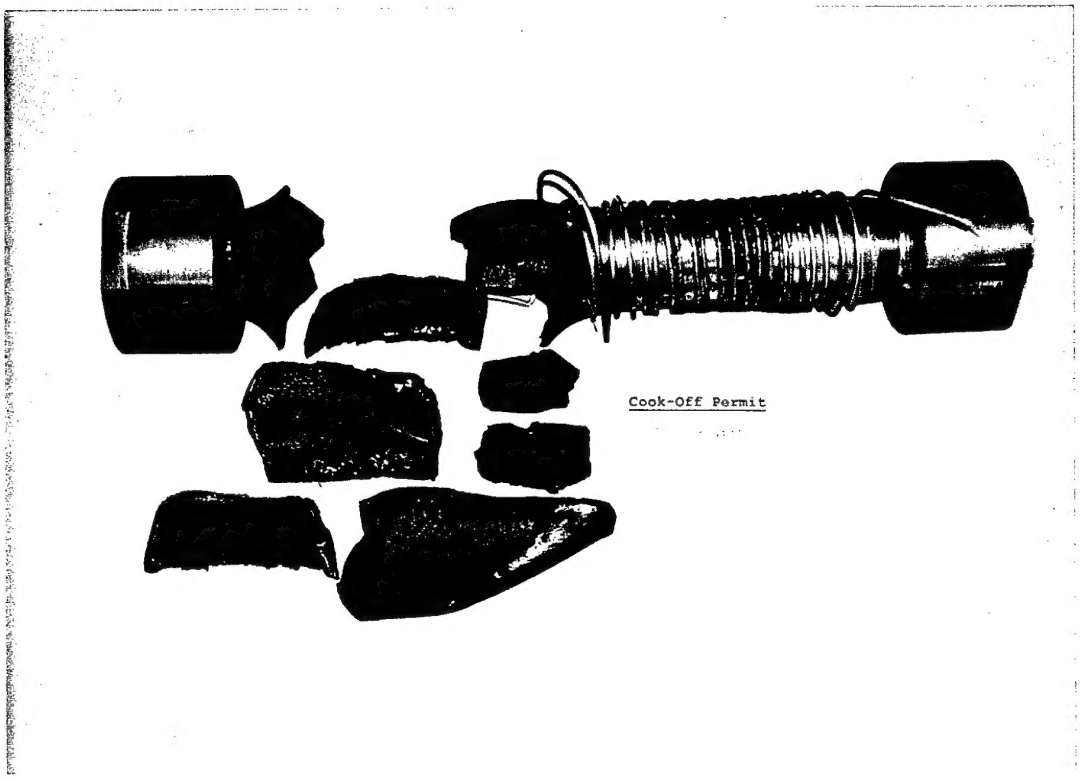

Photo A.3: Fragmentation of the Cook-off experiment with Permit B.

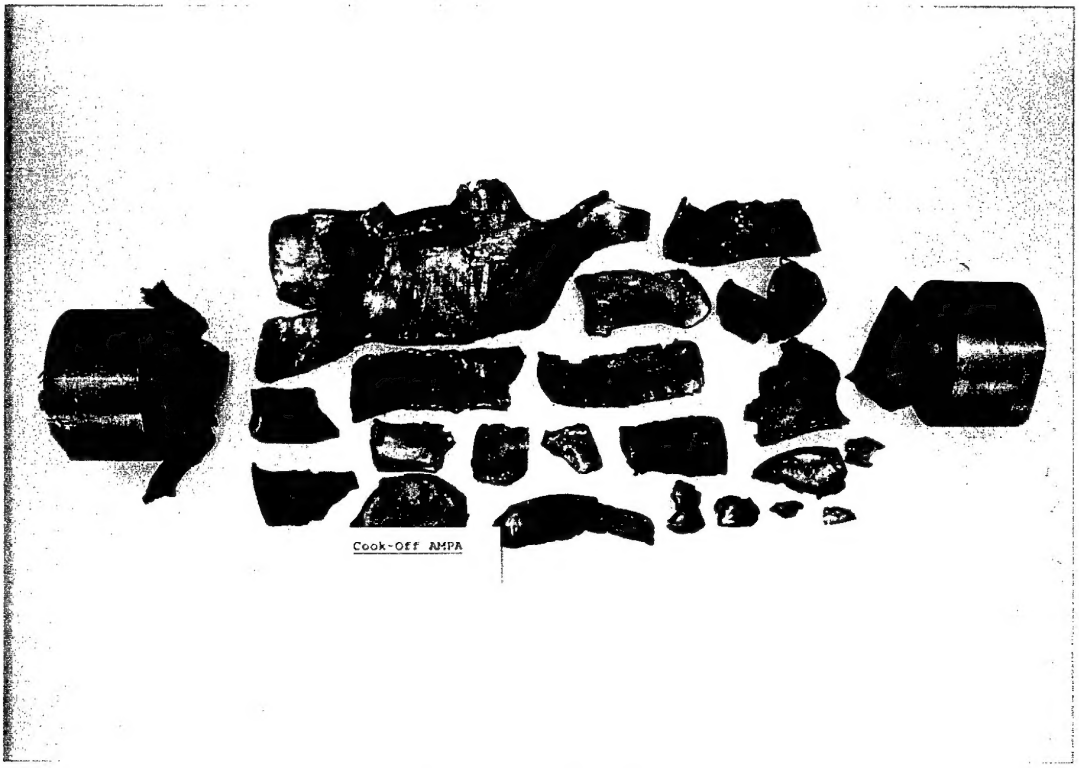

Photo A.4: Fragmentation of a Cook-off experiment with AMPA.

Annex B Calculation of the experimental conduction coefficient

In paragraph 7.6, page 201 of Carslaw and Jaeger [4], we find the one-dimensional equation for the temperature inside a cylinder with a radius *a* when heated at a rate of *k* [°C/s]. After a time $t > 0.86\ \rho Ca^2/\lambda$, the exponential part on the right-handside of the equation is negligible compared to the remaining part of the equation. After this time, the temperature increase per unit of time is *kt* with a time-independent uniform temperature distribution (parabola):

$$\frac{k(a^2 - r^2)\rho\ C}{4\lambda} \tag{B.1}$$

Now we take five temperatures measured by the thermocouple in the HMX-PBX Cook-off experiment at t=1500s (Tmean=90 °C) and fit them with a parabolic equation. Comparison of this parabola with equation (B.1) with C(T)=957.4+2.28182 T, the density ρ=1640 kg/m^3 and the radius a=0.0175 m yields:

$k = 0.0567$ °C/s and $\lambda = 0.3285$ J/msK

Calculation of these parameters for other time values leads to.

Table B.1: Calculated heating rate and conduction coefficient in the HMX-PBX Cook-off experiment.

Time	Heating rate	Conduction coefficient
1500	0.05671	0.3285
2000	0.05721	0.3083
2500	0.05716	0.3030
3000	0.05730	0.301
3475	0.0568	0.311

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15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

After a literature research, the development of the TNO-PML Cook-off test started in 1987. During the years of development, many modifications were made to the test object. In this configuration, test data can be obtained to verify the thermal/chemical Cook-off computer models. Because the general interest is more focused on the level of severity in a Cook-off event, the development of the TNO-PML Cook-off test went in the same direction. Detonation and deflagration to detonation transition (DDT) experiments have been carried out to measure the strain/strain rate during the last phase of the explosion. The results show a trend in the increasing rate of strain of the different phases of the DDT experiment. First results of the Cook-off experiments look very promising, although a quantitative analyses is not yet possible. The radial temperature distribution curves in the centre of the Cook-off experiments reveal interesting information about endothermic and exothermic reaction steps, and melting and crystal phase transitions of the explosive substances. Future investigations will be more focused on the improvement of the strain gauge technique to quantify the level of severity of a Cook-off reaction.

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Strain measurement	Detonation
Cook-off	Strain rate
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